A Review of Virtual Reality Gameplay Mechanisms for Adaptive Dyscalculia Screening

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ABSTRACT

Dyscalculia is a specific learning disorder that affects children's mathematical abilities and is often underdiagnosed due to limitations in conventional screening approaches. Traditional assessment methods are typically static, test-based, and may not effectively capture the diverse cognitive processes underlying mathematical difficulties, particularly in young learners. Recent advancements in virtual reality (VR) and adaptive gameplay offer promising opportunities to develop immersive, engaging, and data-rich screening environments that align with key cognitive constructs associated with dyscalculia. study presents a scoping review of VR-based and game-based tools to identify gameplay mechanisms that can support adaptive dyscalculia screening among early learners. The review is guided by the Malaysian Dyscalculia Instrument (MDI), which defines four core constructs: simple reaction time, short-term memory, arithmetic, and numerosity, including subconstructs such as number sense, dot enumeration, matching items, and number comparison. A structured literature search was conducted across major academic databases, and selected studies were analysed based on platform type, gameplay mechanics, adaptive features, and alignment with these constructs. The findings indicate that while existing tools demonstrate strong potential in enhancing engagement and embedding assessment within interactive gameplay, most focus primarily on intervention rather than diagnostic screening. Additionally, construct coverage is often incomplete, with limited integration of reaction time and fine-grained numerosity skills. Adaptivity is commonly implemented through level-based progression rather than real-time, construct-driven adjustment. This study contributes by proposing a conceptual mapping framework that aligns gameplay mechanics with validated cognitive constructs and highlights design considerations for developing adaptive VR-based dyscalculia screening tools. The findings provide direction for future research toward more comprehensive, engaging, and diagnostically robust screening solutions.

Keywords: Dyscalculia, virtual reality, MDI constructs, adaptive gameplay

INTRODUCTION

Dyscalculia is a specific learning disorder that affects the acquisition of basic arithmetic skills despite normal intelligence and conventional instruction [1]. It is estimated to affect approximately 3–6% of the global population [2], with similar prevalence reported in Malaysia, where studies indicate rates of 5.5% among primary pupils and 4% in VR-based screening contexts [3]. If not recognised early, affected children often experience repeated failure in mathematics, increased anxiety, and reduced academic confidence, highlighting the importance of early identification and support.

Developmental dyscalculia typically emerges in early childhood and can persist into adulthood if left unaddressed, impacting educational and career outcomes [4][5]. Early screening is therefore crucial to minimise long-term academic and psychosocial challenges [6][5]. However, traditional screening approaches remain limited. Paper-based assessments are often disengaging and may induce anxiety [7], while many educators lack adequate knowledge to recognise dyscalculia [8]. Consequently, many children are not properly assessed and are instead labelled as weak in mathematics. Existing tools are also often narrow in scope and lack flexibility, with limited validation in accurately identifying at-risk learners [9]. For example, the Butterworth Dyscalculia Screener primarily focuses on numerosity and does not provide a comprehensive theoretical framework for broader mathematical cognition [10].

These limitations have led to increasing interest in game-based and adaptive approaches for dyscalculia screening. Adaptive gameplay enables real-time adjustment of task difficulty based on learner performance, providing a more personalised assessment experience [11][12]. Digital games such as Graphogame Math and The Number Race have demonstrated improvements in numerical skills among learners with mathematical difficulties [13]. Additionally, studies have shown that children with dyscalculia who engage with serious games in virtual environments perform arithmetic tasks more efficiently compared to traditional approaches [14].

Within this context, immersive virtual reality (VR) has emerged as a promising medium for next-generation dyscalculia screening. VR provides interactive and multi-sensory environments that enhance engagement and reduce distractions, while enabling the capture of detailed performance data such as reaction time, accuracy, and behavioural patterns. Previous studies have reported improvements in engagement [15] and cognitive skills such as working memory [16] and have highlighted VR's potential for both assessment and intervention [17]. By embedding assessment tasks within gameplay, adaptive VR systems can reduce test anxiety while maintaining optimal challenge levels [18][14].

The Malaysian Dyscalculia Instrument (MDI) provides a structured framework for dyscalculia screening based on four cognitive constructs: simple reaction time, short-term memory, arithmetic, and numerosity, including number sense, matching items, dot enumeration, and number comparison [10][19]. These constructs capture multiple dimensions of mathematical cognition and offer a strong foundation for developing adaptive screening tools.

Developing effective VR-based screening systems requires collaboration between game developers, educators, and cognitive experts to ensure alignment between gameplay, pedagogy, and cognitive theory [20]. Despite the potential of VR and adaptive gameplay, existing tools are largely designed for intervention rather than screening and often lack comprehensive alignment with validated constructs.

This study therefore aims to review VR-based and game-based tools to identify gameplay mechanisms suitable for adaptive dyscalculia screening. It contributes by proposing a conceptual mapping framework that aligns gameplay mechanics with validated cognitive constructs, providing guidance for the development of more effective and engaging screening tools.

LITERATURE REVIEW

This section reviews the theoretical and empirical foundations that inform this scoping review. It first outlines how dyscalculia has been conceptualised and why construct-based screening is important for early identification. It then introduces the Malaysian Dyscalculia Instrument (MDI) and its core cognitive constructs, followed by a discussion of serious games, adaptive gameplay, stealth assessment, and immersive VR/AR environments in learning and assessment. Finally, it presents the conceptual lens used in this review to map existing digital tools against MDI constructs, platform characteristics, and adaptivity features, thereby clarifying the gap that motivates the present study.

Dyscalculia and The Need for Early Screening

Dyscalculia is a specific learning disorder that affects mathematical abilities in children and can persist into later schooling if it is not detected early. Many children remain undiagnosed because conventional screening tools are often delivered in controlled settings, require specialist administration, and may not reflect how children naturally engage with numbers during everyday learning activities. Early screening is therefore important to identify children who are at risk and to support timely intervention. In addition, screening that can distinguish between different underlying cognitive weaknesses is valuable because dyscalculia is not a single-symptom condition and may involve difficulties across multiple cognitive processes [21][22][19].

Cognitive Constructs for Dyscalculia Screening based on The Malaysian Dyscalculia Instrument (MDI)

This subsection focuses on the cognitive foundations of dyscalculia screening as operationalised in the Malaysian Dyscalculia Instrument (MDI). Rather than treating dyscalculia as a single, global deficit, the MDI decomposes mathematical cognition into four main constructs that span processing speed, memory, numerosity, and arithmetic skills. The following subsections describe each construct in turn, including simple reaction time, short-term and working memory, numerosity and its subconstructs, and arithmetic. This provides the theoretical basis for later mapping VR and game-based tools to specific screening targets.

Simple Reaction Time

Simple reaction time refers to psychomotor speed in responding to a visual stimulus. In the MDI, this is tested through tasks where children press a button as soon as a dot appears on the screen. This construct represents baseline cognitive and motor response latency, which is important because delayed response time may confound performance on other numerical tasks. Slow reaction time can therefore affect the interpretation of difficulties in more complex screening components and may indicate broader processing-speed issues relevant to learning performance [21][10].

Short-Term Memory and Working Memory

Short-term memory, including visual working memory, is the capacity to hold and manipulate information briefly. The MDI evaluates this by presenting sequences of dot patterns and asking children to recall or compare them after a short delay. Working memory is critical for manipulating numerical information in real time, especially during calculation and multi-step problem solving [23]. Deficits in working memory have been consistently linked to weaker arithmetic achievement and reduced problem-solving effectiveness, suggesting that memory limitations are a meaningful contributor to dyscalculia-related performance [24].

Number Sense

Number sense reflects a natural ability to estimate and compare quantities without relying on counting. Theoretical grounding is often linked to Butterworth's (2002) numerosity model, which describes an Approximate Number System (ANS) present from birth. Children with dyscalculia are reported to have a weaker or less precise ANS, leading to difficulties in quantity discrimination even in simple visual tasks [22][19].

Matching Items

Matching items involves one-to-one correspondence, which is foundational to counting because each object in a set must be mapped to one number. Difficulties in establishing correspondence can contribute to inaccurate enumeration and errors in judging whether two sets are equivalent in quantity. These challenges are often observed among learners with dyscalculia and may appear even when more basic counting routines have been taught [25].

Dot Enumeration

Dot enumeration is a structured counting task that evaluates counting fluency and subitizing, which is the

rapid, accurate recognition of small quantities. Although some children with dyscalculia may eventually count correctly, they often do so with excessive time and cognitive effort. This pattern suggests weaknesses in symbolic processing efficiency and increased reliance on limited working memory resources during quantity processing [25][22].

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Number Comparison

Number comparison tests understanding of numerical magnitude by asking children to identify which of two numbers is larger. Research suggests that children with dyscalculia have a less precise "mental number line," which can lead to errors or delayed responses even with relatively small number sets. This weakness affects both non-symbolic magnitude processing and later symbolic comparisons [26][19].

Arithmetic

Arithmetic tasks involve verifying the correctness of simple equations and are used to measure the automaticity of fact retrieval and symbolic manipulation. This construct is often a central problem area for children with dyscalculia because difficulties in retrieving number facts and applying basic operations can persist despite instruction. Delayed or inaccurate responses indicate weaknesses in operational understanding and memory retrieval processes relevant to early mathematics development [22][27].

Summary of MDI Construct Coverage and Implication for Digital Screening

Overall, the four MDI constructs provide a multidimensional view of mathematical cognition by capturing speed, memory, foundational quantity processing, and operational arithmetic skills. The structured implementation of these constructs enables screening for specific patterns of difficulty rather than producing a single general indicator. The MDI is particularly relevant in the Malaysian context because its construct design and task structure are aligned with regional needs and provide a clear theoretical basis for adapting screening into technology-assisted formats [10].

Digital Game-Based Assessment for Learning Difficulties

While traditional instruments such as the MDI provide structured, theory-driven screening, there is growing interest in using digital games and immersive technologies to assess learning difficulties in more engaging ways. This subsection reviews key strands of work on serious games for learning support and assessment, adaptive gameplay for personalised challenge, and stealth assessment for unobtrusive data collection. It also considers how VR and AR environments can strengthen screening by embedding cognitive tasks in realistic, interactive scenarios. Together, these strands highlight both the opportunities and limitations of game-based approaches for dyscalculia-related assessment.

Serious Games for Learning Support and Assessment

Modern digital learning environments increasingly use serious games to support learning, training, and health-related outcomes. Serious games are digital games designed for purposes beyond entertainment, especially education and cognitive skill development [28]. Within dyscalculia-related contexts, serious games are often positioned as tools to improve foundational mathematics skills while keeping children engaged through interactive tasks. However, many existing math-focused serious games emphasise practice and intervention rather than diagnostic screening, which limits their value for early identification.

Adaptive Gameplay Mechanisms for Personalised Challenge

Adaptive gameplay refers to real-time or structured adjustment of task difficulty and progression based on learner performance. Rooted in Vygotsky's zone of proximal development, adaptive games aim to maintain an optimal balance between challenge and ability by tailoring content dynamically [29]. For example, The Number Race adjusts numerical distance and presentation time to match a child's ability level [30]. In immersive environments, adaptive gameplay can scaffold difficulty across 3D tasks by modifying quantities, time constraints, distractor levels, or task complexity depending on error patterns. Such mechanisms are relevant to dyscalculia screening because they can help identify the learner's threshold of competence within specific cognitive constructs.

Stealth Assessment and Behavioural Data Capture

Stealth assessment embeds assessment within game interactions, enabling continuous evaluation without overt testing [29]. This is useful for young learners because it can reduce anxiety and improve task persistence while capturing behavioural indicators such as response time, error types, strategies, and completion patterns. In Physics Playground, for instance, gameplay behaviours such as tool selection and problem-solving pathways have been used to predict learners' conceptual understanding without explicit tests [31]. This approach aligns with dyscalculia screening goals because it supports subtle measurement of numerical cognition through naturalistic interaction. However, the main limitation is that stealth metrics still require strong validation against established screening instruments to ensure that the captured behaviours reliably represent the intended constructs [20].

Why VR and AR can strengthen screening contexts

Virtual reality can enhance immersion, engagement, and ecological validity by situating numerical tasks within interactive environments that resemble real-world contexts [32]. For example, quantity comparison or counting can be embedded in meaningful scenarios such as selecting items, matching objects, or completing simple missions rather than responding to flat-screen prompts. VR and AR also enable richer data collection through interaction logs, spatial behaviour, and embodied responses. These affordances make VR and AR promising for construct-based screening when aligned with validated frameworks such as the MDI, particularly if adaptive gameplay and stealth assessment are designed to map directly onto specific cognitive constructs [29][10].

Mapping Dimensions for Reviewing VR and Game-Based Tools

To support a structured mapping of the literature, this review adopts a conceptual lens that focuses on how digital tools align with dyscalculia screening requirements. The mapping is based on dimensions that are relevant to both cognitive screening and game/VR design. These include the platform type (VR, AR, 3D game, mobile game), the purpose of the tool (screening versus intervention), the MDI construct coverage (simple reaction time, short-term memory, numerosity subconstructs, and arithmetic), and the presence of adaptivity features. Adaptivity is considered not only in terms of whether difficulty changes, but also in terms of how it changes, such as level-based progression, skill-based sequencing, time-based constraints, or task variation [29].

Challenges Commonly Reported in the Literature

Prior studies suggest several recurring challenges in applying game-based and immersive approaches for learning difficulties. First, many tools emphasise motivation and practice outcomes but provide limited construct-level interpretation for screening decisions. Second, adaptive mechanisms are sometimes implemented without clear linkage to validated constructs, which weakens interpretability. Third, although VR and AR enhance engagement, accessibility barriers remain due to hardware cost, space, and technical support requirements in school settings, especially in developing regions [32]. These challenges highlight the importance of construct-grounded design and careful validation when adapting screening instruments into immersive technologies.

Summary and Research Gap Leading to the Scoping Review

The MDI provides a well-defined construct framework for dyscalculia screening in the Malaysian context, capturing response speed, memory, numerosity foundations, and arithmetic performance [10]. At the same time, serious games, adaptive gameplay, stealth assessment, and VR/AR environments offer strong potential to improve engagement, personalise task difficulty, and capture richer behavioural data for screening [29][32]. However, literature indicates that many digital math tools are not designed specifically for dyscalculia screening, and validated mappings between gameplay behaviour and established screening constructs remain limited. This motivates the need for a scoping review to systematically map existing VR and game-based approaches and identify how they align with MDI constructs, adaptivity mechanisms, and screening purposes.

Review Approach

This section describes how the scoping review was conducted, following established guidelines for transparent and reproducible evidence synthesis. It outlines the overall review design, search strategy, study selection and eligibility criteria, as well as the data extraction and analytical framework used to map existing VR and game-based tools to the MDI constructs and adaptivity features.

Scoping Review Design and Rationale

This study employed a scoping review methodology to systematically map the literature on adaptive gameplay mechanisms in virtual reality (VR) and digital games for dyscalculia screening among early learners. The review followed the PRISMA-ScR guidelines [33], which provide a structured framework for documenting search, screening, and selection processes. Scoping reviews are particularly appropriate for broad, emerging topics where concepts and approaches are still evolving, and where the aim is to clarify conceptual boundaries and identify gaps rather than to evaluate intervention effectiveness [34]. In this study, the goal was to locate and characterise any digital tools that align with dyscalculia-related constructs—especially those defined in the Malaysian Dyscalculia Instrument (MDI)—rather than to compare effect sizes across interventions.

Search Strategy and Information Sources

A comprehensive search was conducted across four major academic databases: Scopus, IEEE Xplore, SpringerLink and Google Scholar. Together, these sources cover a large proportion of relevant peer-reviewed literature in education, computing, and interactive technologies (Haddaway et al., 2015). The initial search string was: ("dyscalculia" OR "math disability" OR “mathematic”) AND ("virtual reality" OR "VR") AND ("screening" OR "assessment") AND ("adaptive gameplay" OR "serious game" OR "game"). This query was first run in general academic search engines and then in each database. However, it yielded no results, indicating that highly specific combinations of dyscalculia, VR, screening, and adaptive gameplay are rare in the current literature. To broaden the retrieval, the strategy was refined into three thematic search groups:

- Group A: VR + dyscalculia (intervention or training focus)
- Group B: Game-based (non-VR) + dyscalculia screening
- Group C: Game-based (non-VR) + dyscalculia intervention or training

Each group had tailored search strings targeting combinations of “dyscalculia” or “mathematic” with terms such as “virtual reality”, “game” or “serious game”, and “screening”, “assessment”, “diagnosis”, “intervention”, “training” or “learning”. The initial and broadened search strategies, including focus areas, search strings, purpose, and results, are summarised in Table I.

Table I. Initial and broadened search strategies used in the scoping review

Search Group	Focus Area	Search String / Keywords	Purpose	Results
Initial	VR + Dyscalculia + Screening	(“dyscalculia” OR “math disability” OR “mathematic) AND (“virtual reality” OR “VR”) AND (“screening” OR “assessment”) AND (“adaptive gameplay” OR “serious game” OR “game”)	To identify papers directly matching all constructs: VR-based, adaptive, for dyscalculia screening	0
Group A	VR + Dyscalculia (Intervention or Training focus)	(“dyscalculia” OR “mathematic”) AND (“virtual reality” OR “VR”) AND (“intervention” OR “training” OR “support” OR “learning”)	To include papers on VR used to support dyscalculia, even if not focused on screening	1
Group B	Game-based (non-VR) + Dyscalculia Screening	(“dyscalculia” OR “mathematic”) AND (“game” OR “serious game”) AND (“screening” OR “assessment” OR “diagnosis” OR “early detection”)	To include papers that focus on screening dyscalculia using digital or serious games, even without VR	2
Group C	Game-based (non-VR) + (Intervention or Training focus)	(“dyscalculia” OR “mathematic”) AND (“game” OR “serious game”) AND (“intervention” OR “training” OR “support” OR “learning”)	To include papers that support dyscalculia using digital or serious games, even without VR or not focused on screening	2

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The broadened search produced:

- Group A: 1 article that met the inclusion criteria
- Group B: 2 relevant articles
- Group C: 2 relevant articles

All search results were exported into a reference management tool for further screening.

Study Selection and Eligibility Criteria

All retrieved references were imported into a reference manager, and duplicate records were removed prior to screening. Eligibility criteria were defined using the Population–Intervention–Focus–Study type logic to ensure that only studies directly relevant to the review question were included.

Studies were included if they met all of the following criteria:

1. Population/Target Scope: Children aged 6-12 years.
2. Intervention/Purpose: Studies evaluating or describing a digital or virtual tool (including VR/AR or video games) aimed at supporting mathematics learning, especially tools designed for screening, assessment, intervention, or training related to dyscalculia.
3. Focus: The tool addressed at least one of the MDI constructs, such as simple reaction time, short-term memory, arithmetic, or numerosity (number sense, matching items, dot enumeration, and number comparison).
4. Study type: Formal publications such as peer-reviewed journal articles, conference papers, academic theses, and book chapters

Exclusion Criteria

Studies were excluded if they met any of the following conditions:

1. Focused on general mathematics education or interventions for typical learners without explicit consideration of dyscalculia or specific learning disabilities.
2. Addressed dyscalculia screening or intervention without any VR or game-based component (e.g., purely traditional pen-and-paper assessments).
3. Were non-empirical (opinion pieces, editorials, or narrative reviews) unless they provided substantial insight into available tools; such sources were used only for background if needed.
4. Targeted adult populations or university students rather than children.
5. Not available in English or did not provide full-text access due to resource constraints.
6. Represented duplicates or superseded results; in cases of overlapping publications, only the most comprehensive source was retained.

Screening Process

The study selection followed a two-stage screening process, consistent with PRISMA-ScR guidelines and illustrated in the PRISMA-ScR flow diagram (Figure 1).

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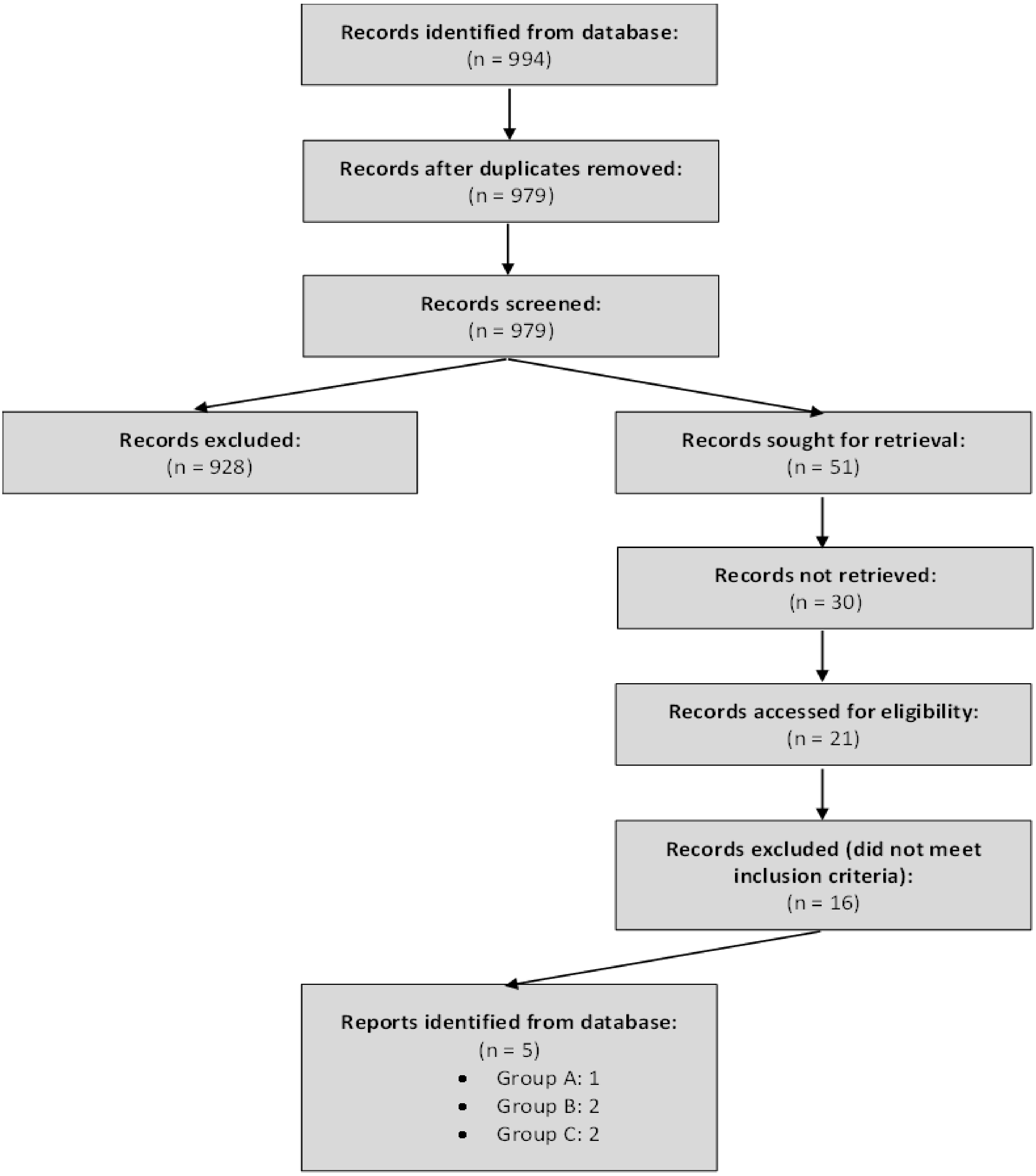
Fig. 1. PRISMA-ScR flow diagram



Following the PRISMA-ScR framework, the study selection process was carried out systematically and is summarised in Figure 1. The database search across Scopus, IEEE Xplore, SpringerLink, and Google Scholar initially identified 994 records. After removing 15 duplicate records, 979 records remained for title and abstract screening. At this stage, 928 records were excluded because they were not relevant to dyscalculia, mathematics learning difficulties, or digital, game-based, VR, or AR approaches. This left 51 records for retrieval, of which 30 could not be retrieved in full text. The remaining 21 records were assessed for eligibility against the predefined inclusion and exclusion criteria. For records that passed the initial screening, full-text versions were obtained and evaluated against the inclusion and exclusion criteria. Each article was assessed for alignment with the target population, the presence of a digital or game-based tool, and coverage of at least one MDI-related construct.

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Studies that did not satisfy all inclusion criteria during the full-text check were excluded. Of these, 16 studies were excluded because they did not meet the required scope, population, tool type, or construct alignment criteria. As a result, five studies were included in the final synthesis, comprising one study from Group A, two studies from Group B, and two studies from Group C. This systematic screening procedure was conducted in line with scoping review best practices to ensure that the final set of included studies directly addressed the research question. The following dimensions were recorded:

- Simple title, author(s), and year
- Platform type (e.g. VR, AR, 3D desktop game, mobile game)
- Mapped MDI constructs (simple reaction time, short-term memory, numerosity subconstructs, arithmetic)
- Adaptivity features (e.g. progressive difficulty, discrete levels, real-time adjustment)
- Mechanism of adaptivity (e.g. level-based progression, time constraints, puzzle variation, skill-based sequencing)
- Primary purpose (screening versus intervention/support)
- Target age group

In addition, qualitative notes were taken on gameplay mechanics, assessment logic, and any reported evidence on learning or screening outcomes. These elements were used to identify overarching themes and gaps, such as:

- Whether adaptive gameplay elements were used for personalised difficulty adjustment
- How VR or AR immersion potentially benefited learners with dyscalculia
- What evidence existed regarding the accuracy or validity of these tools in identifying mathematical difficulties

This extraction and coding process provided the basis for the comparative analysis reported in Table II.

Table II Comparative analysis of VR/Platform Mapped to MDI Constructs and adaptivity features

Simple title, author and year	VR/ Platform	Mapped MDI Constructs	Adaptivity Features	Mechanism of Adaptivity	Purpose	Target Age Group
Virtual Math Learning Environment [35]	3D Game	Short-Term Memory, Number Sense, Arithmetic, Matching Items	Progressive difficulty, skill-based mini-game sequencing	Level-based	Intervention	7–10 years
ATHYNOS AR Game [36]	AR	Number sense, arithmetic, number comparison	Discrete difficulty level, task variation	Level-based	Intervention	7-9 years
CheckDysc [37]	Game	Simple reaction time, numerosity, arithmetic	Puzzle	Level-based	Screening	Preschool children
3D Dyscalculia Assessment Game [20]	3D game	Arithmetic	Puzzle	Level-based	Screening	~6-7 years

Countdown VR [38]	VR	Arithmetic, Short-Term Memory, Number Sense	Real-time problem generation, puzzle, time constraints	Level-based	Intervention	9–12 years

In total, five studies met all inclusion criteria:

- One VR-based game,
- One AR-based game, and
- Three non-VR serious games or 3D environments designed for screening or intervention related to dyscalculia or low mathematics performance.

These studies span various platforms and purposes and collectively cover different subsets of the MDI constructs. They are summarised in Table 2. The patterns emerging from these studies form the basis of the findings and synthesis presented in Section 4.

FINDINGS AND SYNTHESIS

This section presents the results of the scoping review. It first provides an overview of the five included tools, then examines how their gameplay mechanics align with the MDI constructs. It then synthesises cross-cutting themes related to engagement, adaptivity, assessment approaches, and practical constraints, and concludes with key gaps and implications for future design.

Overview of Reviewed VR Games and Tools

The five tools identified in this review span different platforms (3D desktop, mobile game, AR, and VR) and serve both screening and intervention purposes. Their main characteristics are summarised in Table 2 and briefly described below.

De Castro et al. developed an interactive 3D virtual environment comprising 18 mini games aimed at reinforcing core mathematical skills in children with low mathematics performance. Activities range from number recognition and simple calculations to matching and memory-based tasks, delivered through a desktop-accessible virtual world targeting learners aged 7–10. The environment is not adaptive in real time but uses progressive difficulty and tailored game sequences based on pre-assessed learner profiles. Children who used the platform showed statistically significant gains in post-test mathematics scores compared to peers who received traditional instruction [35].

ATHYNOS is an augmented reality (AR) intervention game for children with dyscalculia in Ecuador. It integrates three mini games that target arithmetic operations, number comparison, and visual search in the real environment. The game runs on a tablet, using AR markers to overlay virtual numbers and manipulatives onto the physical world. Each mini-game includes three difficulty levels and targets children aged 7–9. Evaluations showed that the AR group outperformed those using traditional materials in reaction speed and learning gains. Adaptation is structured and level-based rather than fully dynamic but provides personalised challenge through increasing difficulty [36].

Ariffin developed CheckDysc, a serious mobile game for early screening of dyscalculia in preschool-aged children. The game presents a series of foundational number-skill challenges such as counting, number ordering, and identifying odd versus even numbers, each with ten interactive questions. It is delivered on smartphones and calibrated to the typical mathematical level of 4–5-year-olds. After completing all mini games, the system aggregates performance and issues a simple diagnostic output. Scores below an accuracy threshold (around 30 percent, based on trials) trigger an “at risk” warning and recommend professional assessment. CheckDysc focuses on screening rather than intervention and was evaluated for both usability and its ability to flag dyscalculia risk [37].

Pudjoatmodjo and colleagues introduced the 3D Dyscalculia Assessment Game (3DAG), a serious-game framework designed to identify specific mathematical learning difficulties in young learners. The prototype is a 3D adventure-style "detective" game that embeds assessment tasks such as counting objects and simple addition within an interactive narrative. Children solve everyday scenarios that require quantitative reasoning, for example helping a character collect the correct number of items. The tool targets first-grade learners (around 6–7 years old) and captures mathematical "misconceptions" during play. Teachers receive feedback on each child's specific weaknesses. Lab-based evaluations showed high engagement and positive user experience ratings, although some interface usability issues were noted [20].

Cecotti et al. designed Countdown VR, which simulates the "numbers round" of popular educational game shows in an immersive VR setting. Children receive a set of digits and a target number and must reach the target using arithmetic operations. The game dynamically generates puzzles with varying complexity depending on player success, adjusting the number and size of digits, the target value, or allowed time. Interaction is handled via VR controllers, and studies with children aged 9–12 reported positive engagement in attention and mental arithmetic, with some reports of mild VR fatigue [38].

Together, these tools illustrate diverse approaches to embedding mathematical tasks within interactive environments, with varying degrees of adaptivity and differing emphasis on screening versus intervention.

Mapping Gameplay Mechanism to Dyscalculia Constructs

Mapping the five tools against the MDI constructs shows uneven but promising coverage. As summarised in Table 2, arithmetic and numerosity-related skills are the most consistently represented, while simple reaction time and some numerosity subconstructs receive limited attention.

All five tools include arithmetic in some form. Countdown VR emphasises multi-step mental arithmetic under time pressure, which draws on both arithmetic fact retrieval and procedural fluency. ATHYNOS integrates arithmetic into narrative-based decisions and comparisons. The Virtual Math Learning Environment and 3DAG embed basic calculations into mini-games and story quests, and CheckDysc uses short arithmetic challenges as part of its screening tasks.

Elements of number sense and number comparison are visible in most tools. ATHYNOS includes tasks where children select larger numbers or compare quantities under time constraints. The Virtual Math Learning Environment and 3DAG involve estimation and matching tasks that support intuitive quantity processing, although not always explicitly labelled as number sense.

Short-term memory and working memory are less frequently targeted as primary outcomes but are inherently involved in multi-step tasks. Countdown VR requires children to remember digits and intermediate calculations while planning operations within a limited time. Similarly, memory demands arise in sequence-based or puzzle-style tasks in the Virtual Math Learning Environment and 3DAG, where children must hold quantities or instructions in mind across several steps.

Simple reaction time is directly operationalised only in CheckDysc, which inherits some of the MDI logic by including fast-response tasks that combine numerosity and speed. Other tools sometimes use time limits, but these are usually tied to challenge and engagement rather than designed as measures of pure reaction speed.

Coverage of the finer-grained numerosity subconstructs is partial. Number comparison appears in ATHYNOS and some mini games in 3D environments. However, specific constructs such as dot enumeration and matching items are rarely gamified explicitly in immersive settings. Adaptivity is implemented primarily through level-based progression (for example, increasing puzzle complexity or decreasing time limits) rather than through fine-grained, construct-specific adjustment tied to validated thresholds.

Overall, the mapping suggests that current tools capture important aspects of arithmetic and broad numerosity but do not yet provide a comprehensive, construct-aligned implementation of all MDI components. This limits their diagnostic breadth as screening tools, even when they are effective for practice or engagement.

Cross-Cutting Synthesis of Assessment Dimensions

The included studies also highlight broader issues that cut across tools, including the balance between difficulty and engagement, standardisation and personalisation, implicit and explicit assessment, and constraints related to coverage and accessibility.

Cognitive Difficulty vs Engagement and Real-World Relevance

Traditional instruments such as the MDI prioritise precise measurement of specific constructs under controlled conditions. They use well-defined tasks to assess number sense, working memory, and arithmetic with high interpretability and standardisation [21][10][22]. However, these assessments are typically delivered in formal settings that may not reflect how children naturally interact with numbers during play or daily activities. In contrast, the reviewed VR and game-based tools focus strongly on engagement and contextual realism. Examples include narrative-driven tasks in 3DAG and the use of AR to count or compare objects in the physical environment in ATHYNOS. VR scenarios such as Countdown VR simulate game-show style challenges that feel familiar and motivating. These designs can make numerical tasks more meaningful and may reduce test anxiety, especially for children who are reluctant to engage with formal assessments. The trade-off is that high engagement can sometimes make it more difficult to isolate specific cognitive constructs unless the game mechanics are deliberately mapped to them.

Standardisation vs Personalisation in Adaptive Gameplay

Static instruments like the MDI offer fixed item sequences and scoring rules, which support standardised comparisons across learners and contexts [19]. Game-based environments introduce opportunities for personalisation, for example through level-based progress, modified time limits, or dynamically generated puzzles. In the reviewed tools, adaptivity is mostly implemented in a structured, level-based fashion. For instance, ATHYNOS and the Virtual Math Learning Environment use discrete difficulty levels, and 3DAG structures tasks within a narrative that becomes more complex as players progress. Countdown VR provides more dynamic adaptation through on-the-fly puzzle generation and time adjustment based on performance. This adaptivity can help keep tasks within a child's zone of proximal development and reveal thresholds of ability more precisely. At the same time, variable difficulty complicates comparability. If two learners encounter different puzzles or time constraints, direct comparison of scores becomes less straightforward unless the adaptation algorithms are tightly linked to the underlying constructs and calibrated carefully. This tension between standardisation and personalisation remains a key design challenge for construct-based screening games.

Implicit vs Explicit Assessment and Validation

Stealth assessment uses in-game behaviours as indicators of underlying skills, which can reduce test anxiety and create a more continuous picture of learning [29]. Elements of stealth assessment appear in tools like 3DAG, where error patterns and in-game choices provide insight into misconceptions, and in the Virtual Math Learning Environment, where progression through mini games reflects mastery of different skills. However, the reviewed studies provide limited evidence of formal validation of these in-game metrics against established instruments such as the MDI. CheckDysc is a partial exception because it was explicitly calibrated to identify "at risk" learners using thresholds derived from pilot data with dyscalculic children. In general, the subtlety of implicit assessment can become a weakness when behavioural indicators are not carefully aligned with theoretical constructs or when validation against traditional measures is lacking [20]. Future work needs stronger validation studies that compare game-derived indicators with MDI scores or other standardised assessments.

Construct Coverage and Accessibility Gaps

Across the tools reviewed, construct coverage is skewed towards arithmetic and broad numerosity, with less attention to simple reaction time, dot enumeration, and matching items. This reflects a wider pattern in mathematics games which focus on symbolic skills and curriculum-linked content while underrepresenting lower-level perceptual and correspondence-based constructs that are central to dyscalculia models [10][13]. As a result, the diagnostic potential of these tools as comprehensive screeners is limited.

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In addition, accessibility and scalability remain practical concerns. VR solutions such as Countdown VR require head-mounted displays, space for safe movement, and technical support, which may be challenging in many schools, particularly in developing regions [32]. AR and 3D desktop games can reduce some barriers but still depend on devices, connectivity, and teacher readiness. These constraints must be considered when proposing VR-based tools for widespread dyscalculia screening.

Summary of Gaps and Implications for Future Design

Taken together, the findings show that existing VR and game-based tools demonstrate promising features for supporting mathematics learning and, in some cases, for screening dyscalculia. Arithmetic and number sense are well represented, and several tools implement engaging narratives, immersive environments, and level-based adaptivity that can motivate learners and provide rich behavioural data.

At the same time, significant gaps remain. Construct coverage is incomplete, with limited implementation of simple reaction time, dot enumeration, and matching items as defined in the MDI. Adaptivity is often only loosely tied to validated constructs, which reduces diagnostic interpretability. Stealth assessment elements are present but rarely validated against standard screening instruments. Finally, hardware, cost, and infrastructure constraints limit the scalability of VR-based solutions in many school systems.

These gaps suggest that future work should focus on hybrid models that combine the diagnostic accuracy of instruments like the MDI with the motivational and adaptive strengths of game-based and immersive technologies. There is a need for VR and game designs that incorporate the full set of MDI constructs, make adaptation mechanisms explicitly construct-aligned, and include systematic validation against established screening tools. Such designs could lead to next-generation dyscalculia screeners that are both scientifically strong and engaging for young learners.

CONCLUSION

This scoping review examined how virtual reality (VR) and game-based tools have been used to support screening and intervention for dyscalculia and related mathematical difficulties in children. Following PRISMA-ScR guidelines, the search initially aimed to identify tools that combined three key elements: VR, adaptive gameplay, and dyscalculia screening. No studies fully met all these criteria, so the scope was broadened to include serious games and non-VR tools that addressed dyscalculia or low mathematics performance using digital or game-based approaches.

Five tools were identified: one VR game, one AR game, and three non-VR serious games or 3D environments. Across these tools, arithmetic and broad numerosity skills were the most consistently targeted constructs. Some games incorporated level-based or puzzle-based adaptivity, and several embedded tasks in engaging narratives or immersive worlds. However, coverage of the full set of MDI constructs was uneven. Simple reaction time, dot enumeration, matching items, and clearly defined working-memory tasks were rarely implemented explicitly, limiting the diagnostic breadth of these tools for dyscalculia screening.

The review suggests that VR and game-based tools can make mathematical tasks more engaging and less threatening, allowing children to demonstrate their abilities in naturalistic, playful contexts. Elements of stealth assessment and adaptive difficulty are already present and show promise for capturing richer behavioural data. At the same time, there are important gaps in construct alignment, validation, standardisation, and accessibility. Adaptivity is often not tightly linked to theoretical constructs, formal validation against instruments such as the MDI is limited, and VR hardware requirements may restrict large-scale use in many school systems.

Overall, the findings point to the need for next-generation hybrid designs that combine the construct clarity and diagnostic accuracy of tools like the MDI with the motivational, adaptive, and immersive strengths of VR and serious games. Future work should focus on designing gameplay that explicitly covers all relevant constructs (including reaction time, memory, and fine-grained numerosity subskills), implementing adaptivity that is clearly mapped to these constructs, and conducting validation studies against established screeners. By doing so, researchers and developers can create VR and game-based tools that are not only engaging, but also strong and practical for early dyscalculia screening and support.

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